USB Type-C ENGINEERING CHANGE NOTICE

Title: Section 6.6.5 USB Active Cable Electrical Requirements for LRD-based cables
Applied to: USB Type-C Specification Release 2.0, August 2019 with Active Cable Retimer ECR

Brief description of the functional changes proposed:
Adds new section 6.6.5.4 to describe electrical requirements for redrived based active cables Adds new section Appendix G to describe the procedure to extract the pulse response from sampled data and calculating non-linearity noise of LRD based active cables

Benefits as a result of the proposed changes:
Define requirements for redriver based active cables in order to allow low-cost, low-complexity and long-reach cables to be added to the USB echo-system with minimum risk

An assessment of the impact to the existing revision and systems that currently conform to the USB specification:
Introducing a new cable technology to an already-existing echo-system might results in interoperability issues due to design assumptions in the devices that are already out. This spec aim to identify and mitigate the risks in order to minimize it and keep the risk in a reasonable level. This mean that cable which fail to meet this spec will have interoperability issue, but for the cable which will pass the spec all we can say is that it have a low risk of interoperability in some extreme cases of worst case (for this matter) systems. The justification for taking this risk is the cross-industry desire to allow low-cost, low-complexity and long-reach cables to be added to the USB echo-system and the LRD cable technology is the best known way to go.

An analysis of the hardware implications:
No HW implication assumed in the endpoints. Basic assumption of this spec is that TX and RX spec does not change.

An analysis of the software implications:
No known issues.

An analysis of the compliance testing implications:
A new compliance test will need to be written to test active cables, but no known changes to existing tests on the endpoints are anticipated.

Actual Change Requested

(a). Section 6 Active Cables Page 261

From Text:

6.6.5 USB4 active cable electrical requirements

6.6.5.1 Background

This section describes the electrical requirements and compliance testing for Active Cables. The compliance testing is defined to ensure interoperability in terms of data integrity and electrical specifications enabling the Active Cable to reliably receive an input signal and output a valid signal at its other end.

The active cable types are:

1) Retimer based active cable (this section is covering Retimer based cable for USB4 only, USB3 retimer cable is defined in Section 6.6.4)

2) Linear Redriver (LRD) based active cable (USB3.2 and USB4) (electrical spec not defined yet)

3) Linear Optic based cable (electrical spec not defined yet)

To Text:

6.6.5 USB4 active cable electrical requirements

The requirements in this section are tentative and subject to change. Due to the Covid-19 pandemic, interoperability testing normally done before finalizing requirements has not been possible. Expect that there may be some minor changes to the requirements when interop testing is completed.

6.6.5.1 Background

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The active cable types are:

1) Retimer based active cable (this section is covering Retimer based cable for USB4 only, USB3 retimer cable is defined in Section 6.6.4)

2) Linear Redriver (LRD) based active cable (USB3.2 and USB4)

3) Linear Optic based cable (electrical spec not defined yet)

(b). Section 6.6.5.4, Page xxx

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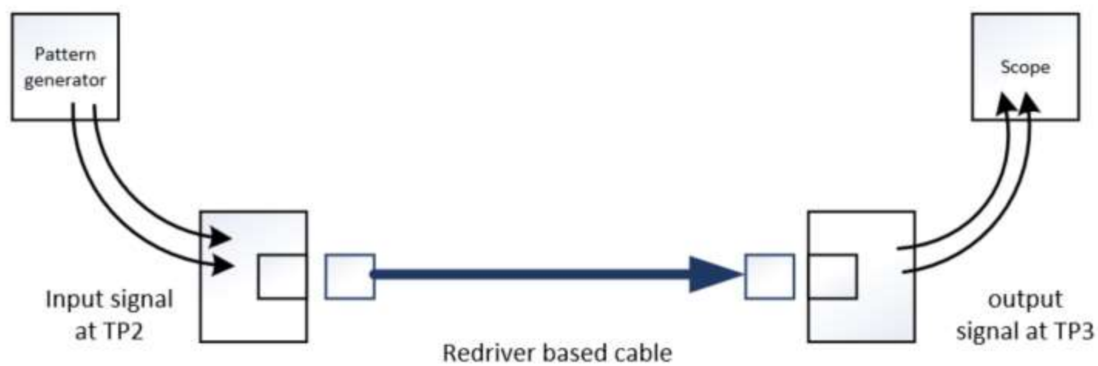
To Text: Insert the new section text below.

6.6.5.4 Active Linear Redriver cable electrical requirements

6.6.5.4.1 Background

Redriver based cable shall be tested as a complete component for compliance.
A Redriver based cable is expected to receive a reference signal (referenced to TP2) defined in this specification and output a signal at the other end with electrical characterization that meets the requirements (referenced to TP3).
As shown in figure 1-1, a compliance USB TypeC receptacle shall be connected to both ends of the cable for injecting and measuring the signal to the corresponding TP2 and TP3 reference points. Details of the Compliance Receptacle and boards can be found in chapter 3.3.6 of USB4 Specification.

Figure 1-1. Redriver cable compliance setup.



Note: the internal placement of the redriver ICs is purposely not mentioned in order to allow full flexibility to the manufacture to develop varies redriver based solutions.

6.6.5.4.2 General implementation notes

This spec is developed while considering the legacy systems and with the intention to avoid electrical interoperability issues, as the LRD based active cables are added to the USB ecosystem in a late phase when a lot of devices are already in the field.

The TypeC interconnect ecosystem is assuming the worst case 1m/2m/0.8m passive cable to be the worst-case connection (for USB3.2, USB4-Gen2 and USB4-Gen3 respectively).
Therefore, it is intended to align the LRD based Active-Cable specifications to the existing passive cable specifications defined in USB Type-C standard, such that the LRD based cable characteristics will be equal or better than these of the worst-case passive cable.
The worst-case passive cable is defined in the USB3.2 and USB4 CTS.
This spec will define the electrical characterization of the LRD based cable that shall be meet in order to obey this requirement.

The LRD cable spec is assuming no change is needed to the existing TX/RX specification of the endpoints PHYs so that compatibility to existing certified USB3 and USB4devices is maintained.

There are few derivative assumptions result from the above assumption regarding the LRD cable implementation:

1) LRD cable is assumed to have no clock mechanism in its datapath (such as CDR).

2) LRD cable is assumed to not have a dynamic amplitude control (such as AGC) to avoid masking the txffe training from the receiver.
3) LRD cable is assumed to not use the training patterns to train itself, especially it is assumed to not block the output data during any phase of the training period.
4) One of the main receiver system assumption is the low-pass-filter nature of the cable, having too equalized cable (i.e. weak LPF characteristic) can lead to interoperability issues. therefore, It is recommended that when developing an LRD based active cable, the cable should be built and tuned in a way that will make it the most passive-cable-like in appose to most equalized cable.

6.6.5.4.2 USB4 Redriver based Cable Compliance Testing

Table 1-1 defines the USB4 Redriver based Cable specifications for USB3.2 and for USB4 Gen2 and Gen3 systems at TP3.
These parameters shall be measured at the Redriver based Cable's output while applying a reference signal at the input as specified in Table 1-2.
A Redriver based Cable shall be tested by injecting several patterns, calibrated to TP2.

Symbol	Description	Min	Max	Units	Conditions
$ILfitatDC$	Defining the ILfit mask for the cable response. the main intention is to keep the cable with LPF characteristic similar to the passive cable.	ILfitatNq+1.5	0	dB	See 6.6.5.4.4
$ILfitatf1$		$ILfitatNq$	$ILfitatDC$	dB	See 6.6.5.4.4
$ILfitatNq$		USB3.2: -6 USB4-Gen2: -12 USB4-Gen3: -7.5	ILfitatDC-1.5	dB	See 6.6.5.4.4
$ILfitatf2$		$ILfitatNq-3$	$ILfitatNq$	dB	See 6.6.5.4.4
$ILfitatf3$		$ILfitatf2-4$	$ILfitatf2$	dB	See 6.6.5.4.4
$ILfitatWB$	Max gain of the cable in the range of DC to f_N		0	dB	See 6.6.5.4.4
OUTPUT_NOISE	Standard deviation of the cable output noise. Combination of all noises beside the non-linearity noise.	See 6.6.5.4.6		mV	See 6.6.5.4.5 and 6.6.5.4.6
SIGMA_E	Standard deviation of the Non-linearity noise measured in the cable output		15	mV	See 6.6.5.4.7
Operating margin	Receiver margin evaluation	3		dB	See 6.6.5.4.10 normative only for USB4-Gen3

Eye mask	Eye mask in the cable output				See 6.6.5.4.11
CM_NOISE	Common mode noise		100	mV pp	See 6.6.5.4.13
IRL	Integrated Return Loss				See 6.6.5.8
IMR	Integrated multi-reflection (integration of ILD -Insertion loss deviation)				See 6.6.5.4.9
OUTPUT_ISI	Managing the response of the cable to be in a certain regular limit				See 6.6.5.4.12

Table 1-1. Redriver cable output Spec parameters

Pattern (all defined in USB4 Specification 8.3.2.1.1)	Swing (referenced to TP2)	Added jitter	TX equalization	SSC	Minimum measurement time	Usage
PRBS15	800mV ptp	NO	NO EQ	NO	20us	Cable gain, non-linearity noise
PRBS15	USB4: 1300mV pp USB3.2: 1200mVpp	NO	NO EQ	NO	20us	non-linearity noise
SQ512	300mV pp	NO	NO EQ	NO	20us	Output noise
PRBS31	As define in USB4 Specification and CTS					Eye mask at TP3

Table1-2. Input signal in TP2 for compliance testing

6.6.5.4.3 Measurement methods

The compliance testing of a cable to this spec will be done based on measurements from both time and frequency domains.

For all time domain spec items, the measured LRD based cable parameters will be compared to the worst-case passive cable supported in each technology (with nominal cable length of1m for USB3.2, 2m for USB4-Gen2 and 0.8m for USB4-Gen3) measured in the exact same setup to reduce testing complexity.
The worst-case passive cable is defined in the active cable CTS.
More details on the measurements methods can be found in the active cable CTS.

6.6.5.4.4 Cable ILfit mask (DC/f1/Nq/f2/f3/WB)

Based on the pulse response extraction from the time domain measurements ($h(n)$) Fourier Transform is used to extract the impulse frequency response $H_{impulse}(f)$.
For the spec parameters calculation, a fitted version of $H_{impulse}(f)$ shall be used.
The pulse extraction and fitting methods are detailed in the active cable CTS and in Appendix A of this document.

$ILfitatDC = 20 * \log_{10}(ILfit(DC))$.

$ILfitatf_1 = 20 * \log_{10}(ILfit(f_1))$.
$ILfitatf_N = 20 * \log_{10}(ILfit(f_N))$.
$ILfitatf_2 = 20 * \log_{10}(ILfit(f_2))$.
$ILfitatf_3 = 20 * \log_{10}(ILfit(f_3))$.
$ILfitat\mathrm{WB} = \max\left(20 \cdot \log_{10}\left(ILfit(f_0)\right)\right), where\ f_0\ is\ in\ the\ range\ of\ DC\ to\ f_N$

$DC = 100MHz$.
$f_1 = f_N * 0.7$
$f_2 = f_N * 1.25$
$f_3 = f_N * 1.5$
$f_N\ for\ USB3.2: 5GHz$
$f_N\ for\ USB4 - Gen2: 5GHz$.
$f_N\ for\ USB4 - Gen3: 10GHz$.

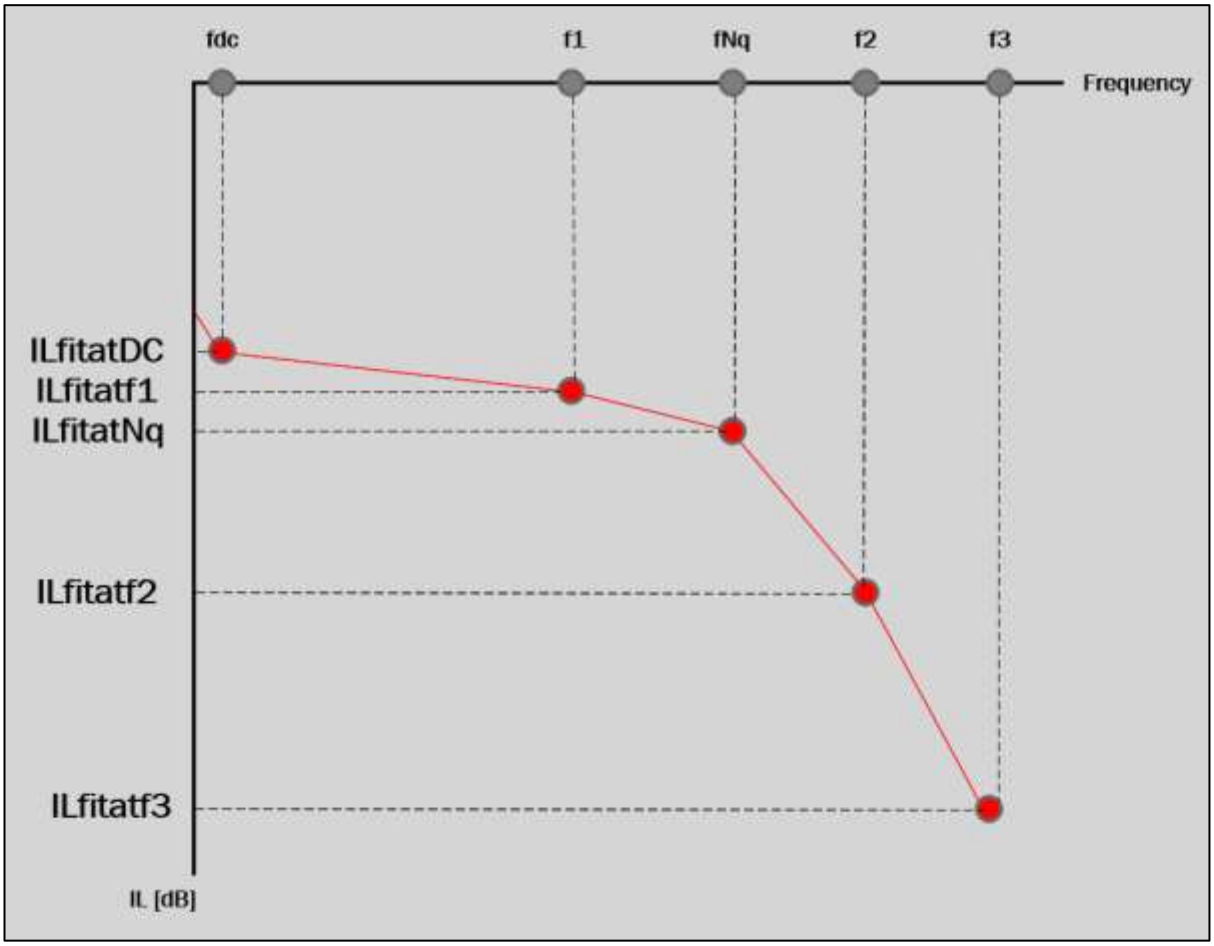


Figure 1 gain parameters specified for the redriver cable

6.6.5.4.5 OUTPUT_NOISE (σ_n)

σ_n is the standard deviation of the uncorrelated additive noise added to the output signal of the redriver active cable. In order to achieve an accurate measurement, the calculation will be done based on low frequency signal (SQ512 pattern) applied to the cable input, with $0.3Vpp$ amplitude.

Since the noise calculation is referred to the receiver input, a 2nd order Butterworth LPF filter with -2dB @Nq shall be applied on the captured wave in order to account to the receiver BW and device side platform.

6.6.5.4.6 OUTPUT_NOISE limit

The limit of OUTPUT_NOISE is defined as function of the IL at Nyquist frequency.
This allow a degree of freedom to the cable developer to trade between the cable's gain and noise.
The limit is defined as:

$$\sigma_{cable} \leq \sqrt{\frac{\sigma_1^2}{10^{\frac{H(f_N)_{PC}-H(f_N)_{RC}}{10}}} - \sigma_1^2} \cdot \frac{1}{\alpha}$$

The following parameters shall be used:

σ_1	2mV
α	0.9
$H_{PC}(f_N)$	USB3.2: -6dB USB4-Gen2: -12dB USB4-Gen3: -7.5dB

Figure 1-2 shows a graph of this function for the given parameters.

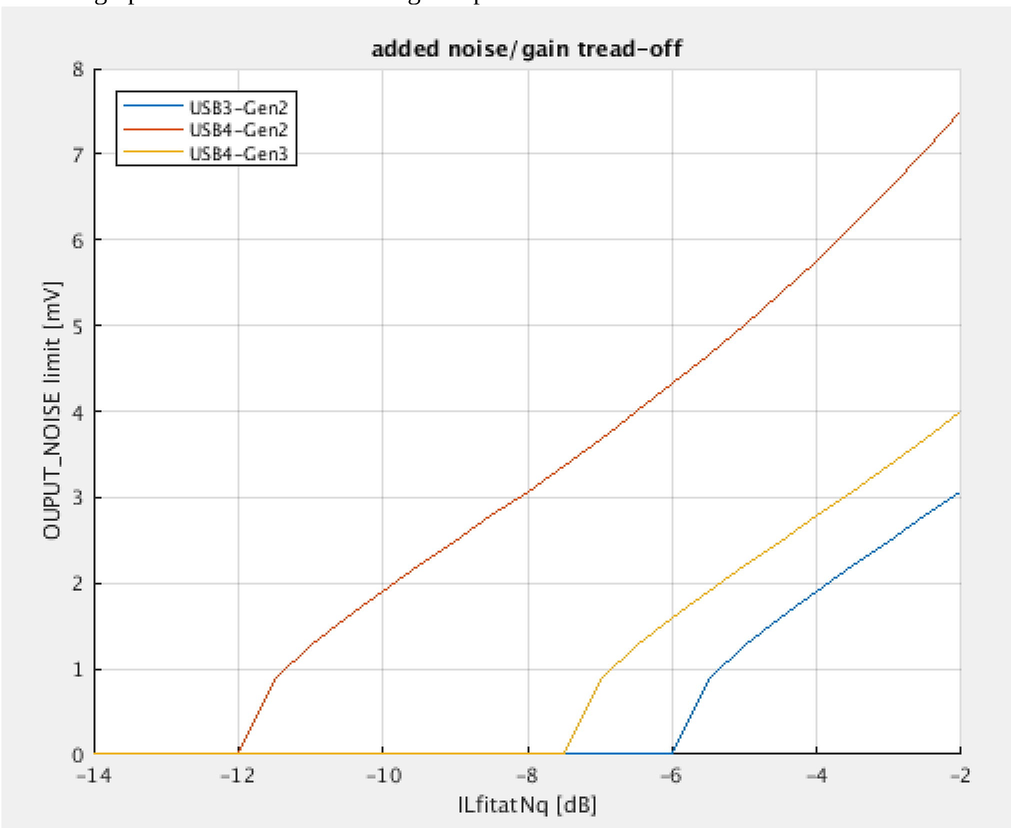


Figure 2 OUTPUT_NOISE limit versus ILfitatNq

6.6.5.4.7 SIGMA_E (σ_e)

σ_e is the standard deviation of the non-linearity related noise added by the redriver active cable.
This measurement shall be performed twice: once with minimum input swing and once with maximum input swing.

Then, $\sigma_e = \max\left(\sigma_{e\,\max swing}, \sigma_{e\,\min swing}\right)$.
Where:
maximum input $swing = 1300mVpp\ (USB4)\ or\ 1200mVpp\ (USB3.2)$.
Minimum $input\ swing = 800mVpp$.
$(compatible\ with\ USB3/USB4\ spec\ \max swing\ definition)$
More details on the calculation of the non-linearity noise can be found in the active cable CTS and in Appendix A of this document.

6.6.5.4.8 Integrated Return-Loss limit (IRL)

IRL term for LRD cable is calculated similarly to the Passive cable, see at 3.7.3.2.4 of this document.
The IRL limit is different in LRD cable and given by the functions in this table:

mode	IRL limit
$USB3-Gen2$:	$IRL \leq 0.046 \cdot ILfitatNq^2 +\ 1.812 \cdot ILfitatNq - 8.784$
$USB4-Gen2$:	$IRL \leq 0.046 \cdot ILfitatNq^2 +\ 1.812 \cdot ILfitatNq - 8.784$
$USB4-Gen3$:	$if(-4dB \leq ILfit@Nq):\ IRL \leq\ -13dB$ $if(ILfit@Nq < -4dB):\ IRL \leq\ ILfit@Nq - 9$

6.6.5.4.9 Integrated Multi-reflection (IMR)

IMR term for LRD cable is calculated similarly to the Passive cable, see at 3.7.3.2.2 of this document.
The IMR limit is different in LRD cable and given by the functions in this table:

mode	IMR limit
$USB3-Gen2$:	$IMR \leq 0.126 \cdot ILfitatNq^2 +\ 3.024 \cdot ILfitatNq - 20.392$
$USB4-Gen2$:	$IMR \leq 0.126 \cdot ILfitatNq^2 +\ 3.024 \cdot ILfitatNq - 20.392$
$USB4-Gen3$:	$if(-4dB \leq ILfit@Nq):\ IMR \leq\ -29dB$ $if(ILfit@Nq < -4dB):\ IMR \leq\ 1.741 \cdot ILfit@Nq - 22.143$

6.6.5.4.10 Evaluating channel operation margin (COM)

Channel operating margin (COM) shall be calculated for cables supporting USB4 Gen3, for evaluating a reference receiver margin based on the cable measured S parameters.
The measurements of the cable and the setting of the associated COM tool is defined in the active cable CTS.

6.6.5.4.11 Cable output eye mask

LRD cable shall meet eye mask limits at its output.
The test setup shall be identical to the USB3.2 and USB4 calibrated receiver test which includes worst case passive cable.
During the test, a reference CTLE, DFE and TXFFE settings shall be tuned according to the USB3.2 /USB4 spec for obtaining the optimal eye.

1) USB3 have fixed TXFFE setting according to the USB3-Gen2 TX spec.
2) USB4 can tune the TXFFE according to the TXFFE preset table in USB4 Spec Table 3-5.

After obtaining the optimal eye with the passive cable, repeat the same measurement with the LRD cable under test, and compare the extracted eyes.
The optimal LRD cable eye shall be meet these criteria:
$LRD\ cable\ eye\ area \geq Passive\ cable\ eye\ area$
AND
$LRD\ cable\ eye\ width > 0.9 *\ Passive\ cable\ eye\ width$

note that the maximum eye height is constraint by the spec item ILfitatWB that prevent active amplification over the entire frequency range.

6.6.5.4.12 Cable OUTPUT_ISI limit

In order to limit the level of irregularity in the active redriver cable due to additional components (IC package etc.), an ISI-Margin test is used to evaluate the regularity of the cable's output.
ISI-margin is calculating both pre-cursor and post-cursor side of the pulse and output single value.
An optimal reference equalization (TXFFE, CTLE, DFE) is applied on the raw captured output signal in order to distinguish between equalizeble and un- equalizeble ISI.

The following steps shall be applied for calculating OUTPUT_ISI:

1) Using the extracted un-equalized pulse response $h(n)$ which described in section 6.6.5.4.4 and mathematically applying the reference TX equalizer, RX CTLE and DFE as define in the relevant spec (USB3.2 and USB4).
   The transmit and receiver equalization shall be selected such that the OUTPUT_ISI is maximized.
2) Using the equalized pulse response $h^e(n)$ to calculate OUTPUT_ISI as the ratio between the signal and the sum of the absolute values of the pre-cursor taps and the post cursor taps from tap 2 and above.

$$OUTPUT\_ISI = 20 \cdot log_{10}\left(\frac{\sum_{n_{pk}-0.5\cdot M}^{n_{pk}+0.5\cdot M-1} h^e(n)}{\sum_{0}^{n_{pk}-0.5\cdot M-1} |h^e(n)| + \sum_{n_{pk}+1.5\cdot M}^{n_{max}} |h^e(n)|}\right)$$

Where,

$h^e(n)$ is the equalized pulse response with M samples per UI

n_{pk} is the equalized pulse response peak index

n_{max} is the last index to be included in the ISI summation, such that
$\{n_{max}: |h^e(n)| < \frac{h^e(n_{pk})}{100} \quad \forall\, n > n_{max}\}$

To simplify the measurement and avoid de-embedding of the cable from the setup, the limit for OUTPUT_ISI is defined to be equal or higher comparing to a worst-case cable measured on the same setup.

6.6.5.4.13 Cable CM_NOISE

CM_NOISE is defined as the maximum peak value of the signal captured in the cable output with common setting to the scope (p+n) and prbs15 data pattern.

The CM_NOISE shall not exceed 100mV.

(b). Section Appendix, Page xxx

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G. Extracting pulse response from sampled data and calculating non-linearity noise

G.1 Overview

The following procedure is used to determine the linear fit pulse response and error for Linear Re-Driver (LRD) based cables.

G.2 Procedure

The transmitter shall be configured to transmit PRBS15 pattern (as defined in USB4 Specification section **4.2.1.3.4**).
Extract the linear fit pulse from the measured waveform using the parameters specified in Table 1-3.
Define an input pattern x(n) to be a single PRBS period of length Nseq and an output signal to be the captured waveform y(n), sampled at M times the signal baud rate.
Average the captured waveform at intervals of 2 PRBS repetitions (2·N·M samples) for filtering out uncorrelated noise.
Correlate the averaged waveform and the reference input pattern for extracting output signal y1(n) aligned to the input pattern x(n) (N·M samples).
Concatenate the post-cursor input pattern corresponding to the first waveform sample at the left of the input vector x(n), and the pre-cursor input pattern corresponding to the last waveform sample at the right of the input vector as following:
$x_1[n] =$ [{x(N-Npost+1), x(N-Npost+2), …, x(N)}, {x(1), x(2), …, x(N)}, {x(1), x(2), …, x(Npre)}]
Zero pad x1(n) to yield xz(n) such that M-1 zeros are inserted between each adjacent entries, before the first entry and after the last entry of x1(n).
Present the output signal y1(n) as the convolution of xz(n) and FIR filter h(n) containing Ntaps·M coefficients:
$y_1(n) = \sum_{k=0}^{N_{taps}\cdot M} x_z(n-k)\cdot h(k)$,

and in matrix representation:

$$y_1^{[(N_{seq}\cdot M)\ x\ 1]} = X_z^{[(N_{seq}\cdot M)\ x\ (N_{taps}\cdot M)]}\cdot h^{[(N_{taps}\cdot M)\ x\ 1]}$$

$$X_z = \begin{bmatrix} x_z(N_{taps}\cdot M) & x_z(N_{taps}\cdot M-1) & \dots & x_z(3) & x_z(2) & x_z(1) \\ x_z(N_{taps}\cdot M+1) & x_z(N_{taps}\cdot M) & \dots & x_z(4) & x_z(3) & x_z(2) \\ x_z(N_{taps}\cdot M+2) & x_z(N_{taps}\cdot M+1) & \dots & x_z(5) & x_z(4) & x_z(3) \\ & \vdots & & & \vdots & \\ x_z(N_{seq}\cdot M) & x_z(N_{seq}\cdot M-1) & \dots & x_z(N_{seq}\cdot M-N_{taps}\cdot M+1) & & \end{bmatrix}$$

Extract the filter h coefficients by applying least-squares fitting:

$$h = [X_z{}^T\cdot X_z]^{-1}\cdot X_z{}^T\cdot y_1$$

where the superscript "T" denotes the matrix transpose operation.
Extract the linear fitting error waveform:

$$e = y_1 - X_z\cdot h$$

Since e have M phases, need to calculate e for each phase.

1) Align the e vector to be in length of M*N.

2) Create a matrix $E^{[NxM]}$ such as $E = \begin{bmatrix} e_1 & e_2 & \cdots & e_M \\ e_{M+1} & e_{M+2} & \cdots & e_{2M} \\ e_{2M+1} & e_{2M+2} & \cdots & e_{3M} \\ \vdots & & & \vdots \\ e_{NM+1} & e_{NM+2} & \cdots & e_{NM+M} \end{bmatrix}$
3) Calculate the standard deviation of each phase. $e_{std} = std(E)$
4) $\sigma_e = \max{(e_{std})}$.
5) The value should be normalized to the input swing: $\sigma_e = \frac{0.4}{TX_{amp}} \cdot \sigma_e$

The following parameters shall be used in the linear fit pulse calculation:

Table 1-3 Linear fit Pulse Extraction Parameters

Parameter	Value
Ntaps	100
Npost	Ntaps-Npre-1
Npre	5
M	8